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DESIGN CONCEPTS TO IMPROVE HIGH PERFORMANCE SOLAR SIMULATOR

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ABSTRACT

In the early eighties ESTEC wanted to start a new large space simulation chamber, its main characteristics were already published (ref. 1). An important part of it was the solar simulator. Compared to the already existing large facilities in the US there were many features and requirements which were changed or tightened. This because of several reasons; roughly they can be divided into two categories: Reasons which give the benefit to the customer and others which give the benefit to ESTEC respectively directly to the operation team.

The main requirements of interest concern:

- the chamber, i.e. the solar beam (it was required to be parallel and horizontal) and the test volume,
- the intensity range,
- the uniformity of the intensity in the reference plane and in the remaining volume,
- the collimation angle,
- the stability of the solar beam,
- the reliability of the facility,
- the efficiency,
- last not least the safety standard and the ease of maintenance.

This paper treats the proceeding and the ideas to raise the well known off-axis concept of solar simulators to this level.

INTRODUCTION

Based on the ESTEC requirements concerning the efficiency, the collimation angle, the light distribution, and the boundary conditions of the existing building, a detailed mathematical study on the basic ray trace parameters was performed. Fig. 1 defines the meaning of the ray trace parameters and table I shows the qualitative impact, specially of the diameter of the integrator, the

projection distance (which is coupled to the throw distance) and the off-axis angle, on the performance parameters. Table 1 clearly shows that there is no straight way to achieve an absolute optimum for every one of these performance parameters in question because a measure which has a positive impact on one parameter influences the next to the negative side. So what one had to do is to choose the design parameters for the best compromise, which still meets the original basic requirements of the ESTEC.

In parallel to these calculations the mathematical shape of the reflector had to be performed to make sure that the integrator size, the efficiency, and the projection distance can be met. Table II shows the original requirements of ESTEC as well as the final outcome as the result of the negotiated compromise. Fig. 1 gives the remaining geometrical data which were of importance for the vessel design and the civil engineering. After having fixed these basic data the vessel design and the civil engineering could nearly independently proceed.

Separately we developed the detailed concepts of the sun simulator components which are discussed below and which are important to achieve the goal.

THE LAMP MODULE CONCEPT

Looking at the intensity distributions of a Xenon arc (ref. 2) one easily notices the high brightness of the arc at the cathode. This means that the light generated by this part must not be wasted, which in return means that the reflector has to surround the arc as far as possible, the hole for the rod of the Xenon bulb must be as small as possible. This of course means that it would not be possible to withdraw the bulb through the reflector. So there are only two ways out: 1: To assemble and to disassemble the Xenon bulb from the outside of the lamp array or 2: to withdraw the Xenon lamp together with the reflector. Because of reasons of ease of maintenance and of safety it was decided to follow the second solution. Of course now it is only logical to withdraw the whole lamp fixture, together with the Xenon lamp and the reflector. This unit is called lamp module. It is shown in Fig. 2. Apart from the ignition device the lamp module contains a sensitive alignment possibility for the arc. By detailed calculations it turned out that efficiency and symmetry of the reflector light distribution is severely affected as soon as the arc is not in its optimum optical position.

Fig. 3 shows the measured difference between an aligned and misaligned arc. In addition it shows the difference in efficiency. Thus the module concept stands for

- ease of maintenance
- good light output
- symmetrical light distribution because of the possibility of alignment
- safety.

THE REFLECTOR CONCEPT

Normally one uses ellipsoids to solve tasks of this kind. The disadvantage of mathematical ellipsoids is their low efficiency for extended light sources and the fact that they produce light distributions with sharp peaks with very steep gradients. Yet the proper mixing function of the typical insect-eye-integrator is only guaranteed if the intensity per lens channel can be assumed to be a constant. Thus a lot of mathematical effort was put into broadening the light distribution in the field lenses plane.

The goal of the mathematical analysis was fourfold:

- To collect a maximum of light of the arc in the usable area of the collector.
- To radiate as much as possible of this collected light into the field lens stop, whereas this stop was limited by the collimation angle and the projection distance.
- To fit the distribution in the integrator plane as far as possible into a rectangular profile.
- To design the light pencil of the reflector to a small divergence. Which means that the reflector diameter is close to the integrator diameter.

Fig. 3b shows a comparison between the calculated light distribution and a measured one.

In addition the reflector concept includes a reflection coating which guarantees high efficiency during a long time. Here Carl Zeiss did not choose a simple Al-layer but an Al/SiO_2-layer. The quartz layer prevents the reflector from quick degradation. It maintains its high average reflectivity of about 85 % for years. Whereas a pure Al-coating very quickly drops down to less than 70 %. The reflector concept stands for

- good efficiency
- little degradation
- broad light distribution in the field lens plane.

THE INTEGRATOR CONCEPT

Looking into the collimation mirror of an off-axis system one can notice that the tank window picture is subject to an elliptical distortion. Detailed ray tracing calculations confirm that the cut view through the beam perpendicular to the chamber axis is an ellipse. The ratio of this ellipse is given by the following formula

$$\frac{1 - T \left(\frac{2 \cos \alpha}{r} - \frac{1}{p} \right)}{1 - T \left(\frac{2}{r \cos \alpha} - \frac{1}{p} \right)}$$

where
T = Throw distance
p = projection distance
T = Target distance
α = off-axis angle

Normally the customer has no benefit of an elliptically shaped beam. The power outside the inscribed largest circle of this ellipse is lost and cannot be included into the efficiency. In the case of the ESTEC - simulator the above ratio is 7,5 % which is a non negligible quantity.

Remembering that the field lenses of the integrator are imaged into the reference plane it is evident to compensate this distortion by a counter elliptical shape of the field lenses. If the optical workshop is equipped with modern numerically controlled optical machinery, the costs of the respective lenses are comparable to normal circular ones.

In designing the remaining lens parameters, i.e. the radii and the thicknesses, all mathematical effort is put into achieving a sharp light distribution in the test plane. This because of two reasons:

1. Every light pencil outside the specified area is wasted power and does not contribute to the efficiency.

2. These "light tails" could hit the shroud system which would demand an additional cooling.

Fig. 4 compares the precalculated light distribution to the measured one in the test plane. Of course the calculated graph takes into account the 55 light channels of the integrator.

Very important mathematical and experimental investigations were done on the thermal loads on the lenses and window. These studies showed that the temperatures of these items can be held below reasonable values, provided the water cooling of the mounts and the gas-stream cooling in the window - integrator area are appropriately designed. It could be shown that these temperatures are to be expected below 370 ^{o}C which means that a $Mg\,F_2$ - coating on the lenses and the window became possible. Such a layer improves the reflectivity from 3,5 % to 1,5 % per surface.

Thus the main goal in designing the integrator was to achieve a high light uniformity and a high efficiency.

THE WINDOW CONCEPT (INCL. MOUNT)

To a smaller extent this concept is an efficiency concept too. Yet this is covered by the note that it became possible to coat it, so the same effect as for the lenses is reached.

However, the window concept is mainly a safety concept. One has to face the following facts:

1. The loads on the window are due to the atmospheric pressure and due to the thermal load

2. The diameter of the window for the LSS came out to 1080 mm which means that it is the largest quartz window of the world.

3. Quartz is a brittle material the strength of which mainly depends on its surface finishing. Even small surface cracks could cause a catastrophe.

In the first step the temperature in the window was calculated based on the amount of light to be absorbed due to the well known material absorption curves and based on a cooling concept, the mode of which takes into account three processes: radiation (in the direction to the chamber, shrouds, and projection lenses), conduction (in the material), convection (transition from the glass to the GN_2). Fig. 5 shows the worst case temperature distribution and in part b the resulting stresses in the materials due to this temperature distribution and an atmospheric pressure of 1.0 bar.

A second step was to test different surface finishing methods and to determine by experiment the stress intensity factors of the respective finishing methods on this material. In dependence of the applied stress and the present length of the cracks those factors govern the crack propagation velocity. Which means that they contain the information which says when a certain crack will result into the failure of the window.

Applying crack propagation theory (ref. 3...7) in the reverse way one can check by a proof test whether a certain item would resist to a given stress for a demanded lifetime (for example 5000 hrs operational time). In practice this means the window is exposed to definite stresses - at every point of the window they are always higher than during actual operation - their exact figure is determined by a crack propagation calculation which takes into account the demanded lifetime. The test equipment which was chosen by us is a pressure vessel as shown in fig. 6. The proof test has to be repeated after the qualification period.

The safety concept includes the design of the window mount. To avoid stresses specially in the area of the edges a belt-mount was chosen similar to those mounts which are normally used for performing interferometric measurements on big optical items. A rough idea of such a mount is given by fig. 8. So the window concept stands for efficiency but mainly for safety.

THE COLLIMATION MIRROR CONCEPT

Due to our good experiences with smaller facilities, for example IABG/-Munich, we followed a concept of a segmented type mirror.

The ESTEC mirror is constructed out of 121 hexagonal segments each of which is GN_2 - cooled (see fig. 9). A special structure was designed to fix the segments via three alignment bolts and one load carrying bolt in a fixed position.

The GN_2 cooling has certain advantages compared to a fluid cooling (in case of failure). For example there is no danger of contaminating a satellite and there is no danger of freezing. The homogeneity of the temperature distribution achieved by this cooling turned out to be perfect. During the acceptance tests of the ESTEC - facility the measured temperature difference between two arbitrary points of the mirror was less than 2 ^{o}C (vertical) and less than 0,5 ^{o}C in horizontal direction. This shows that such a segmented mirror can be ideally temperature controlled, which is a precondition for a stable beam during the whole test. Yet the main arguments which show the advantages of a segmented mirror type are:

- The segments can be coated with high performance layers such as Al/SiO_2. The quartz protection guarantees a high efficiency over years of operation. Contrary to this a full size mirror can only be coated with a simple Al-layer because to our knowledge there are no facilities in the world of that size to do multi-layer coating.

- If one decides to go for a metal mirror the segments can be made out of rolled material whereas big size blanks would usually be castings. Cast aluminum would result in rather poor optical surfaces because of pinholes which cannot be avoided.

- A segmented mirror can be repaired.

- And last not least a segmented mirror type can be easily designed for later enlargement.

Thus the mirror concept stands for long term efficiency and high ease of operation.

THE POWER SUPPLY AND CONTROL CONCEPT

One important feature of a modern solar simulator is the power supply and control.

The assignment of the power supply is to ignite the Xenon lamps and to supply the D.C. within the required ripplefree standard (see table II). The design of the rectifiers was based on well known principles of high power electronics in using the thyristor technique and fitting common marketable components to an optimum solution of the problem. Fig. 7 shows the quality of the D.C.

The assignment of the control is to stabilize the light intensity to a given set level during a solar simulation test. Specially the control has to compensate a lamp failure of a lamp within less than 1 sec without remarkable overshoot (see fig. 7).

A special feature is the "SUMMARY CONTROL". Here only an arbitrary subset of lamps is operated within the control loop, whereas the remaining lamps are operated on constant current conditions. It is within the duty of those lamps

which are included in the summary control to compensate variations of the other lamps or to compensate lamp failures.

The whole solar simulator is safeguarded by a programmable logical control (PLC), SIEMENS type S 105. The PLC does the interlocking by continuously checking the incoming data from the various units, i.e. rectifiers, lamphouse etc. (see fig. 10).

CONCLUSION

By improving several important components of the well known off-axis solar simulator system a considerable step forward was made. Specially the careful mathematical studies on the optics and the thermal side of the problem lead to a highly efficient system with low operational costs and a high reliability. The actual performance of the simulator is significantly better than the specified one, and in particular the efficiency is outstanding. No more than 12 lamps operating at 18 kW are required to obtain one Solar Constant in the 6 m beam.

One of the main conclusions is that contrary to the time the project was started we now know that using sophisticated optics even larger facilities of high performance can be designed without leaving the proven off-axis concept and using a spherical mirror. Vice versa, using high performance optics is a mean to reduce costs at a given size of the beam, because the number of lamps is one of the most cost driving factors in constructing a solar simulator.

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TABLE I

Impact on Measure	Cost of chamber cooling system	Collimation angle	Efficiency	Intensity distribution
Enlargement of integrator diameter	raising investment (lowering operation cost)	negative impact	improvement	positive impact if collectors properly adapted
Enlargement of the projection distance which implicates enlargement of throw distance	cost driving	positive impact	reducing	positive impact
Enlargement of the off-axis angle	cost reducing	negative impact	neutral	negative impact

TABLE II: THE BASIC ESTEC REQUIREMENTS AND THEIR REAL OUTCOME

Requirement	contractual	outcome
Collimation angle	$\pm 2^{o}$	$1,9^{o}$
Test volume	Ø 6 m x 5 m	6,05 m x 6 m
Intensity range	0.65...2,7 kW/m^2	0.1...3.5 kW/m^2
Variation of the intensity in the test plane	± 4 %	± 3%
Variation in the remaining test volume	± 6 %	± 4 %
efficiency	> 12 %	> 18 %
ripple of the intensity p.t.p	0.5 %	0.5 %
Stability during 400 hrs	0.5 %	less 0.5 %
In case of a lamp failure: reaction time for the control to reachieve the old intensity level:	5 sec	0,2 sec
Redundancy	A failure of 2 lamps must not have an impact on the shape of the intensity distribution	7 lamps less do not affect the shape of the intensity distribution
Reproducibility	± 1 % of the intensity distribution profile during 400 hrs	less 1 %

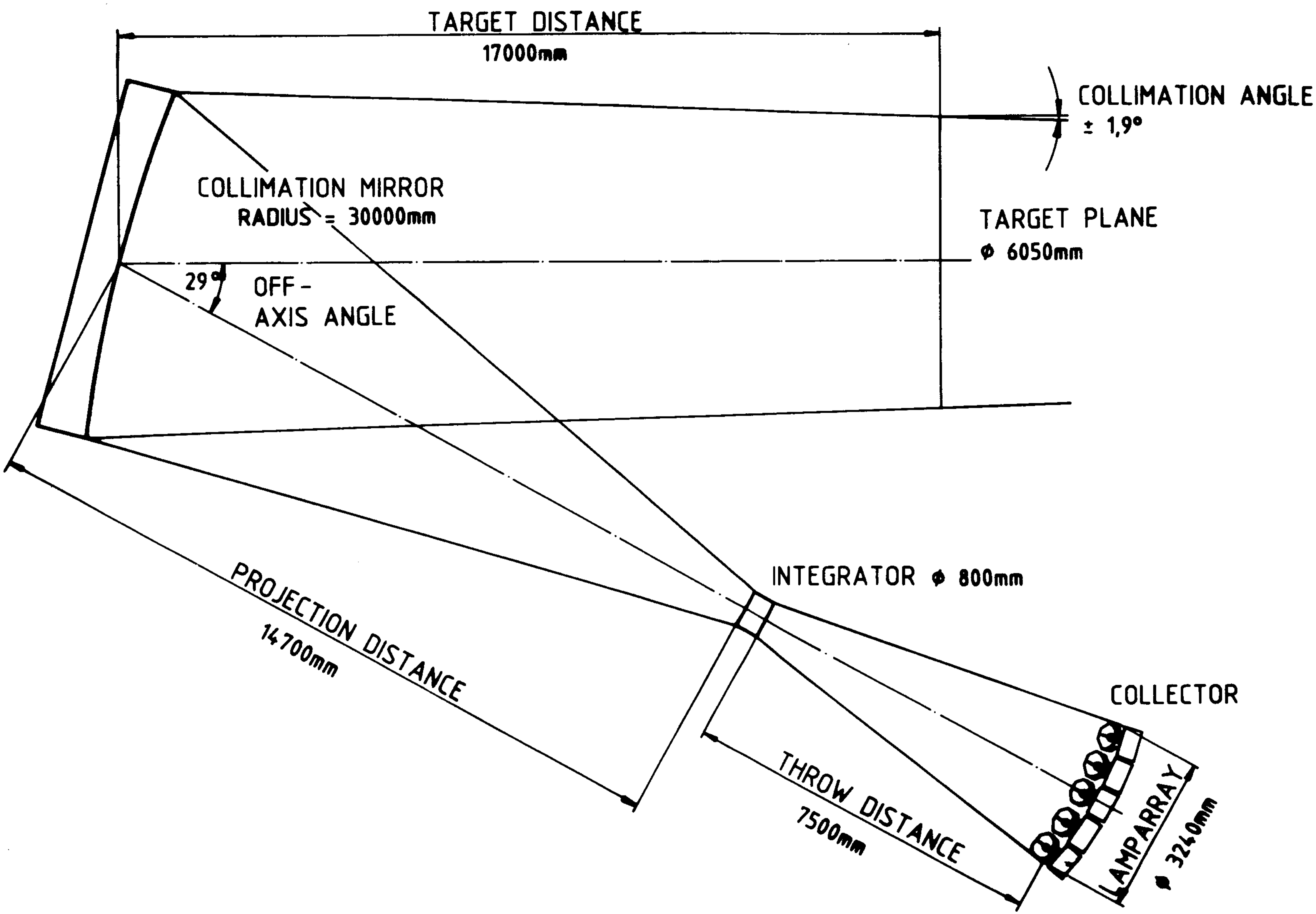

Figure 1. Optical ray trace and basic design data

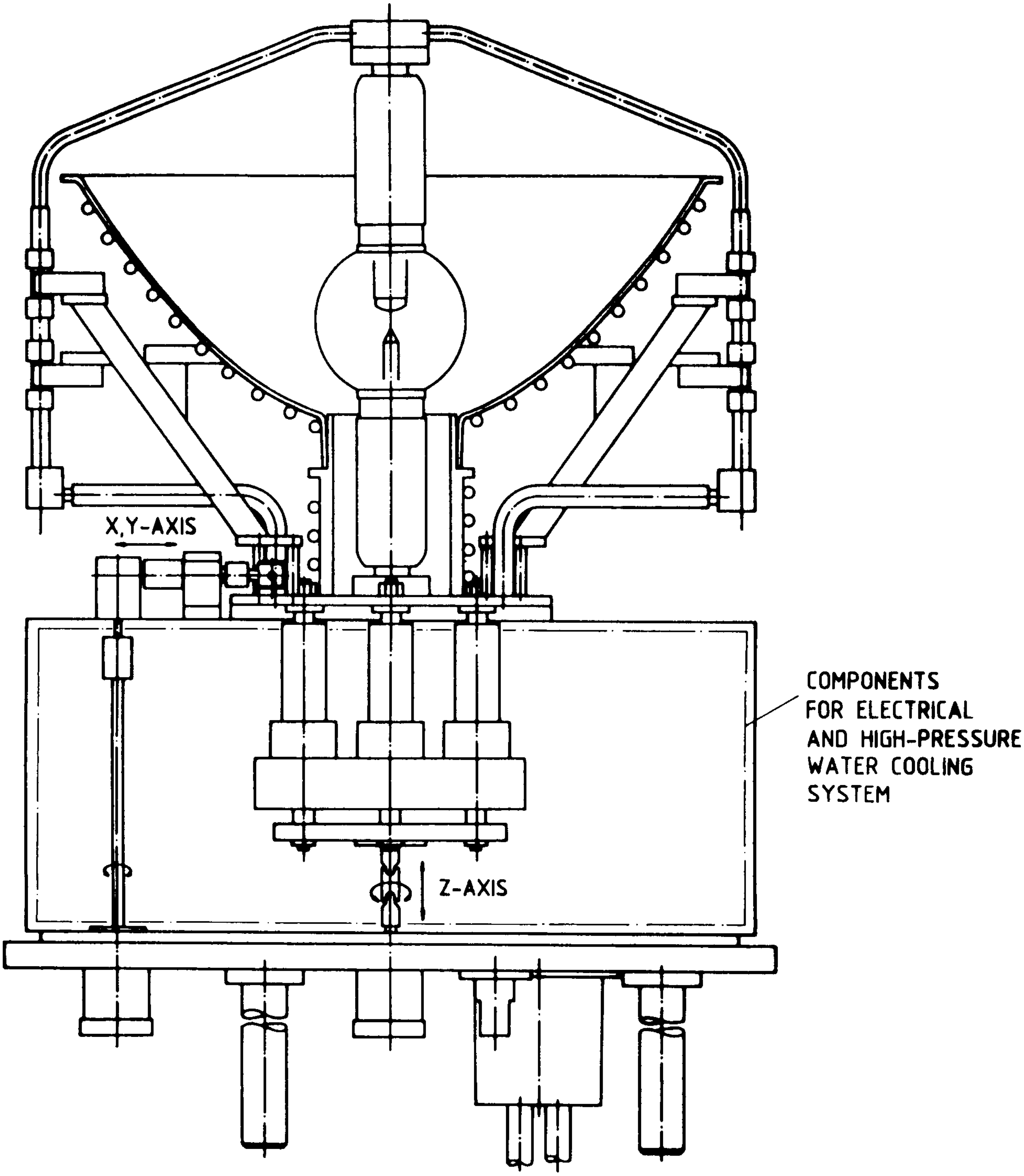

Figure 2. Lamp module design

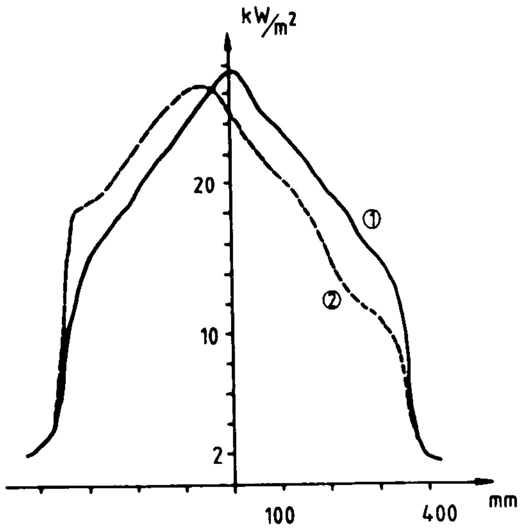

FIG. 3a:
① CORRECTLY ALIGNED ARC
② MISALIGNED ARC

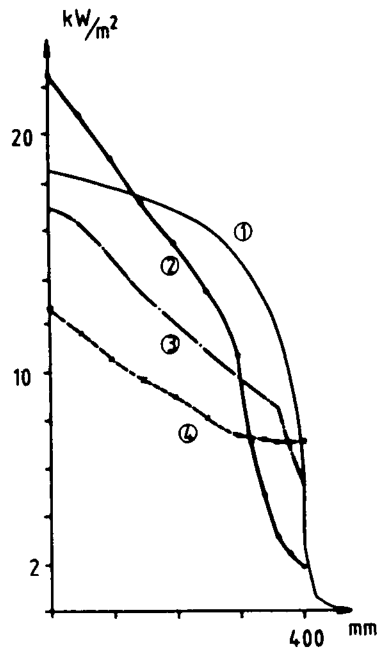

FIG. 3b:
① THEORETICAL GRAPH
② ③ ④ MEASURED GRAPH IN DIFFERENT Z-POSITIONS

Figure 3. Light distribution in the integrator plane

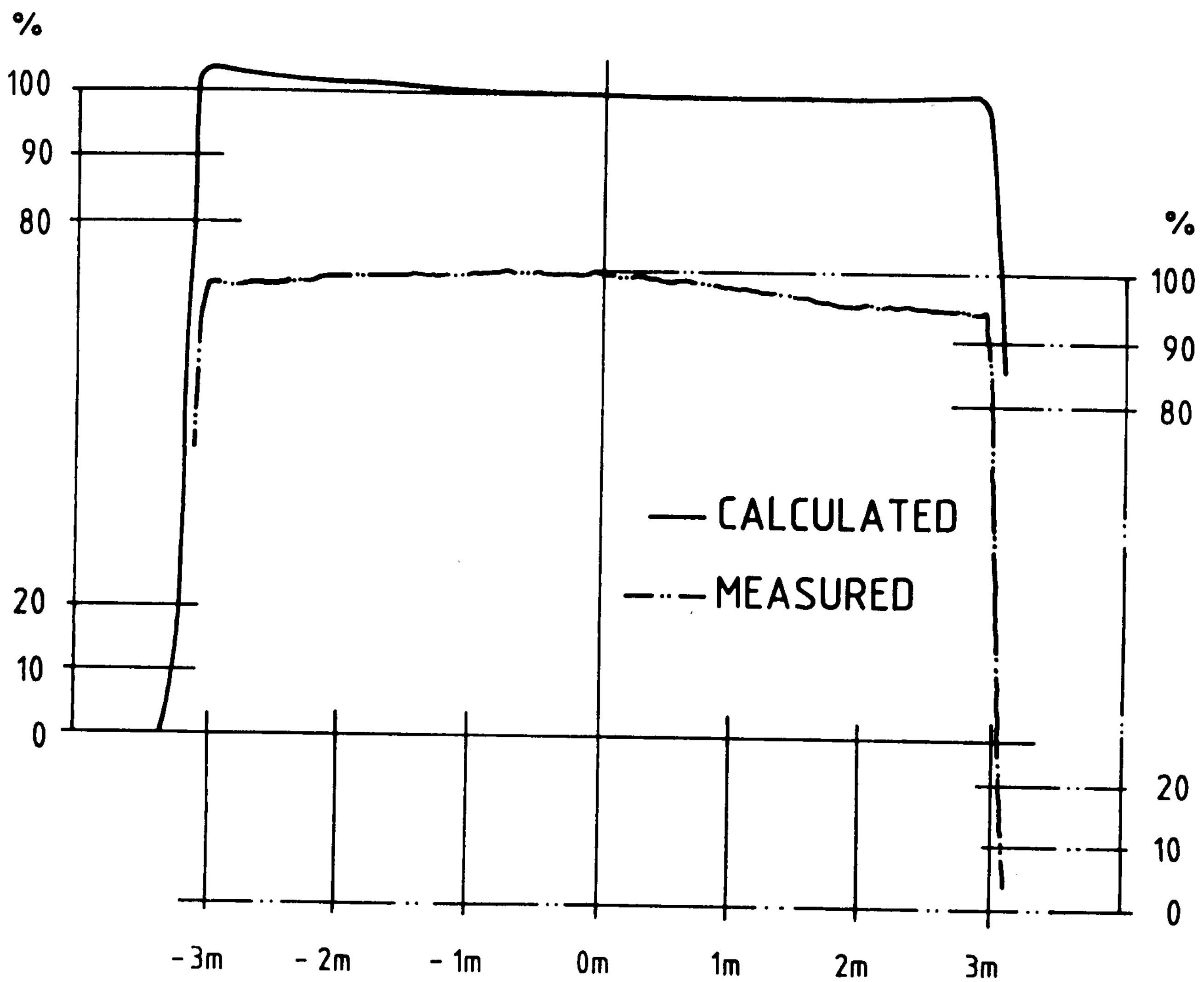

Figure 4. Light distribution in the reference plane

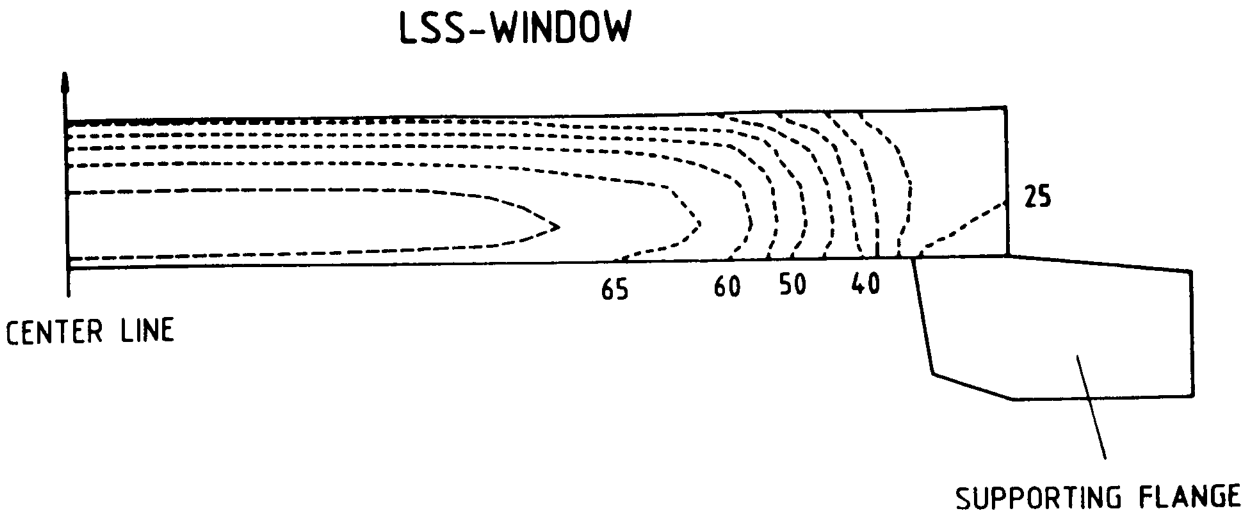

Figure 5a. Temperasture distribution [°C] in the window

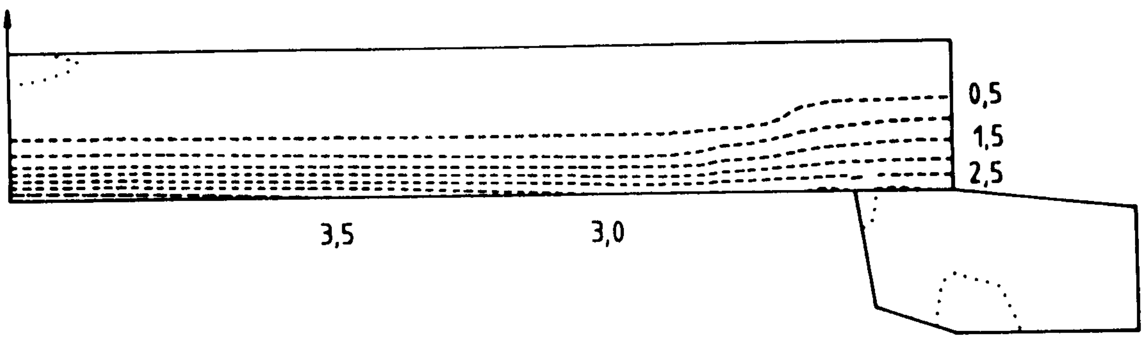

Figure 5b. Stress distribution [MPa] in the window

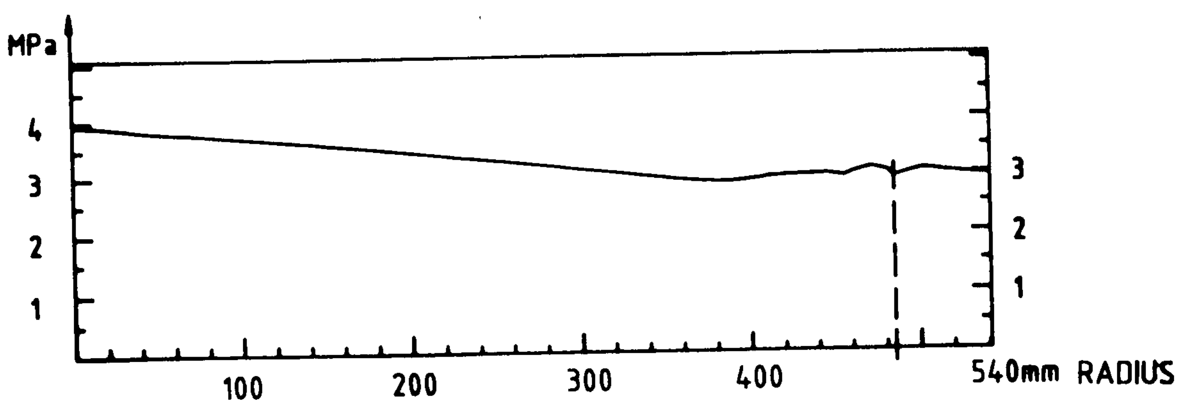

Figure 5c. Stress distribution on the window surface

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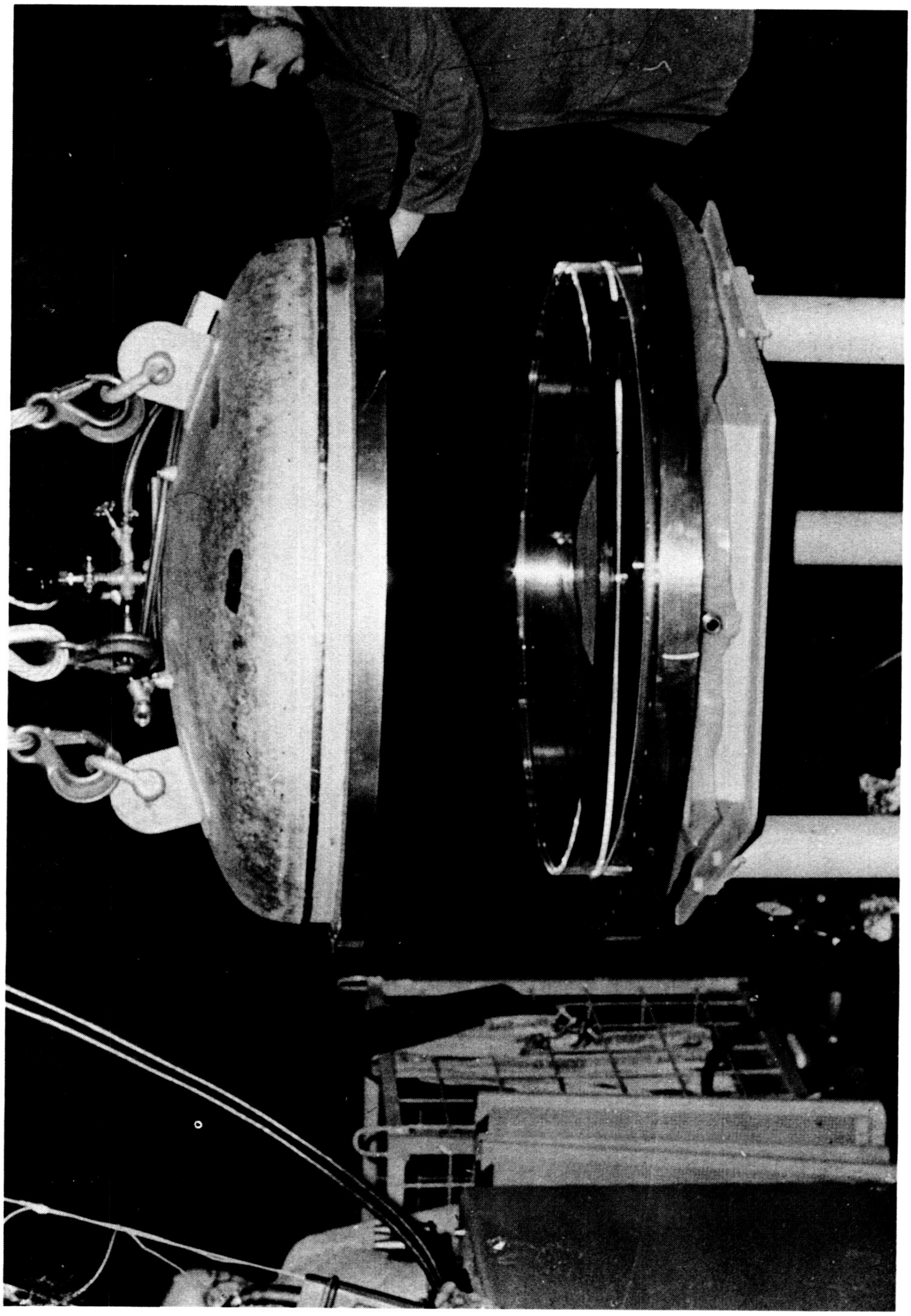

Figure 6. Proof test device

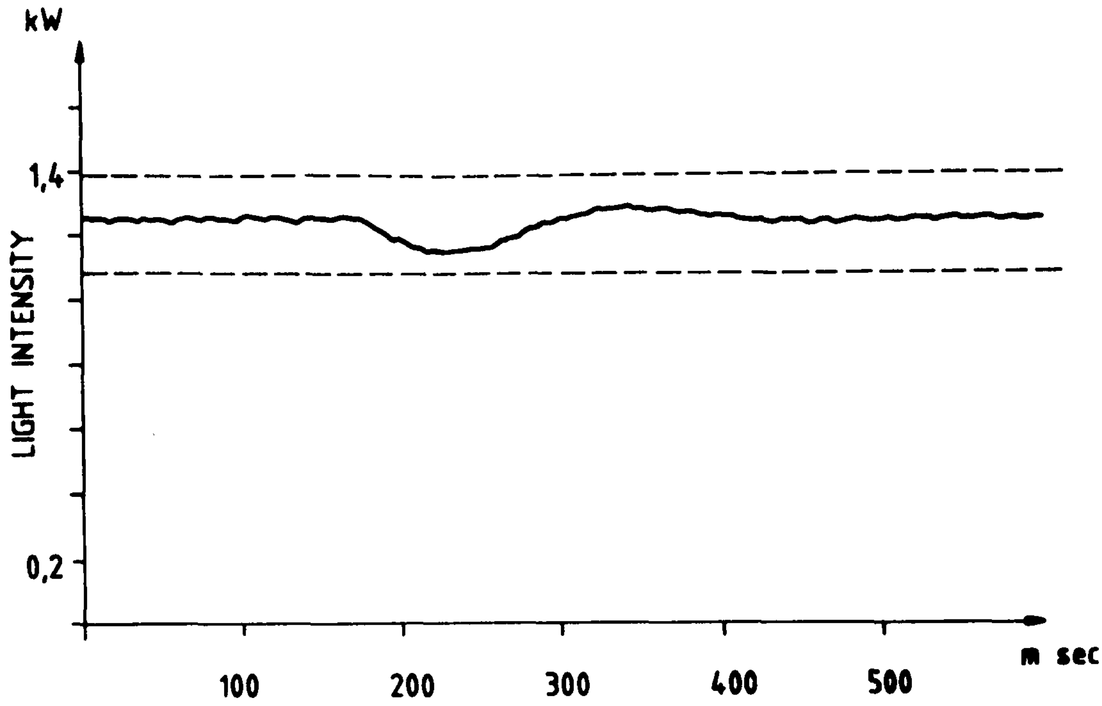

Figure 7a. Reaction of the summary control in case of a failure of 2 lamps

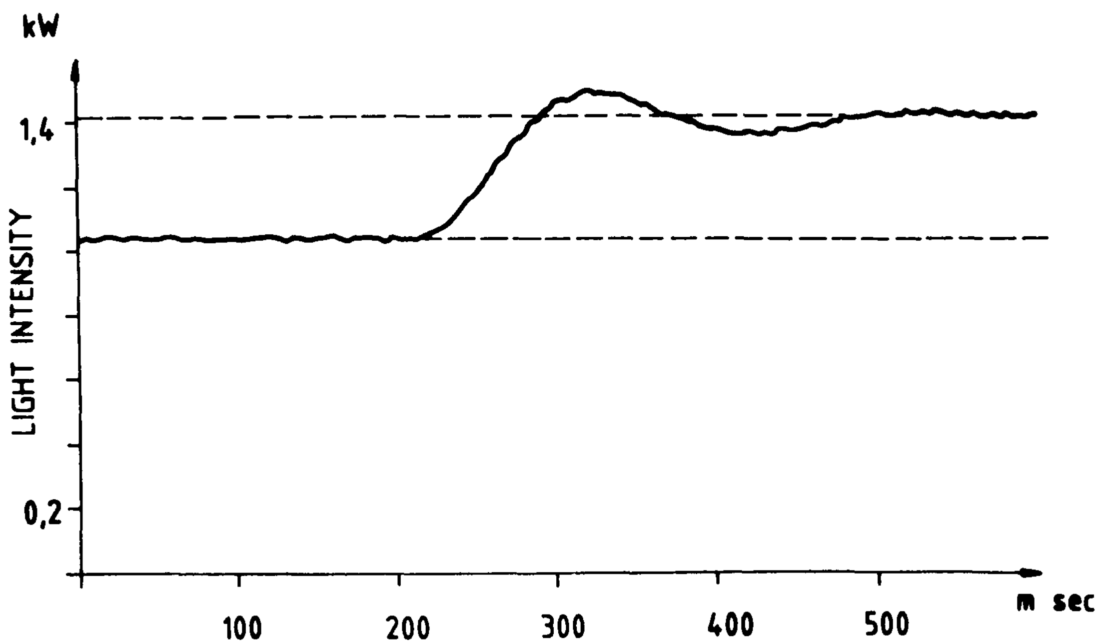

Figure 7b. Control behavior when changing power level

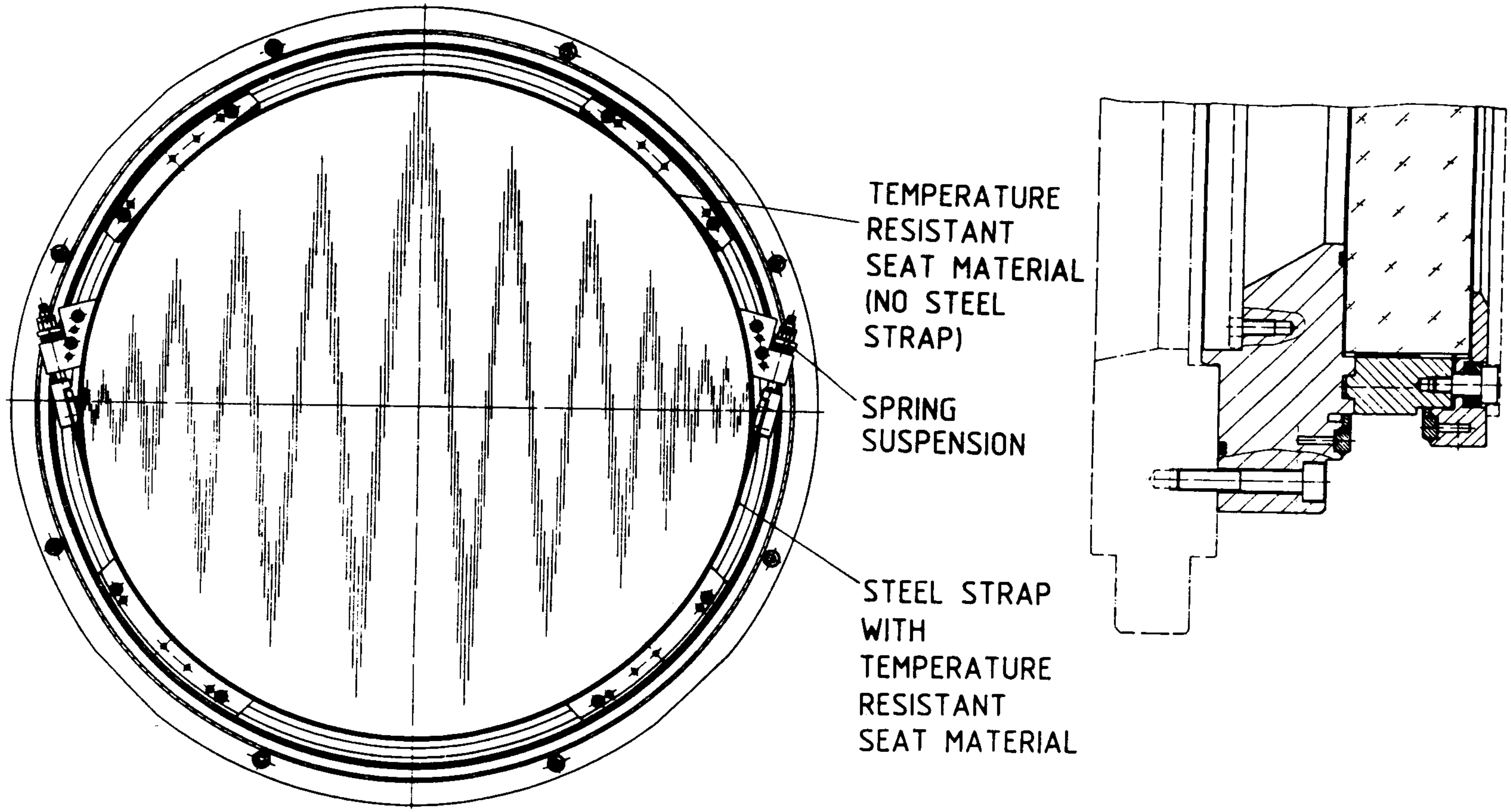

Figure 8. Design principle for the belt mount of the window

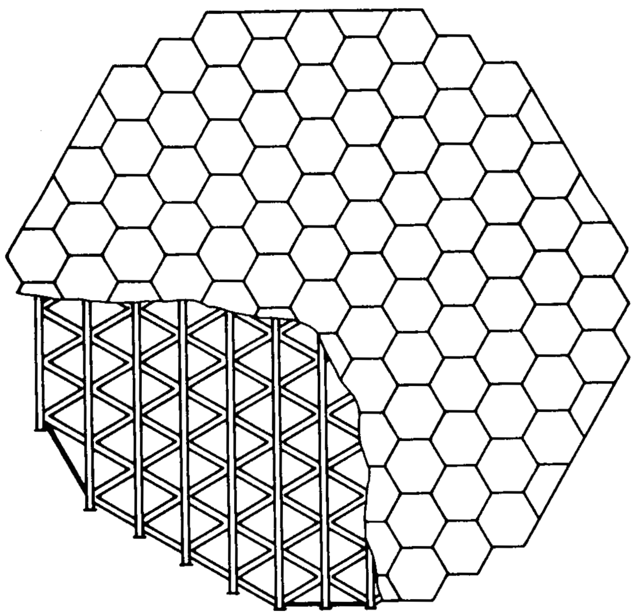

Figure 9. Design concept for the segmented collimation mirror